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USE OF THE CONTOUR METHOD TO DETERMINE AUTOFRETTAGE RESIDUAL STRESSES
A Proposed Experimental Procedure

Anthony P. Parker[1] and Edward Troiano[2]

[1]Defence Academy of the United Kingdom, University of Cranfield
[2]Benét Laboratories

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ABSTRACT

This work proposes a methodology for the determination of residual stresses in a long section of swage-autofrettaged gun tube by employing the relatively new contour method (CM). The CM involves careful cutting of a component, usually using electric discharge machining (EDM). The main experimental challenge during CM cutting is to minimize further yielding in order to ensure that the stress-relief process is essentially elastic. A methodology for minimizing such yielding is proposed. It is shown that CM could be used alone, or in combination with existing X-ray and/or neutron diffraction methods.

INTRODUCTION

Experimental measurement of residual stresses within pressure vessels, in particular gun tubes, has made good progress over the past six years. One convincing and consistent series of results for gun tubes consists of a set of X-ray and neutron diffraction (ND) experiments commissioned by Benet Laboratories' Fatigue and Fracture Analysis facility. These are reported in reference [1], Underwood et al.

The common feature of these experiments is that they were conducted on axially thin (quasi plane stress) ring specimens cut from much longer gun tubes. A recent paper [2] quantifies the differences in residual stresses between an intact long tube with significant axial stresses and an axially thin ring with zero axial stresses after it has been cut from the tube, see Figure 1(a) and 1(b). It is the release of axial stresses within the tube during ring cutting that 'kills' the axial stresses in the tube and modifies the associated hoop and radial stresses. The specimens behave (predominantly) elastically during such cutting and hence the released axial stresses, if known, could be superposed elastically upon those measured in the ring to determine the entire stress field in the intact tube.

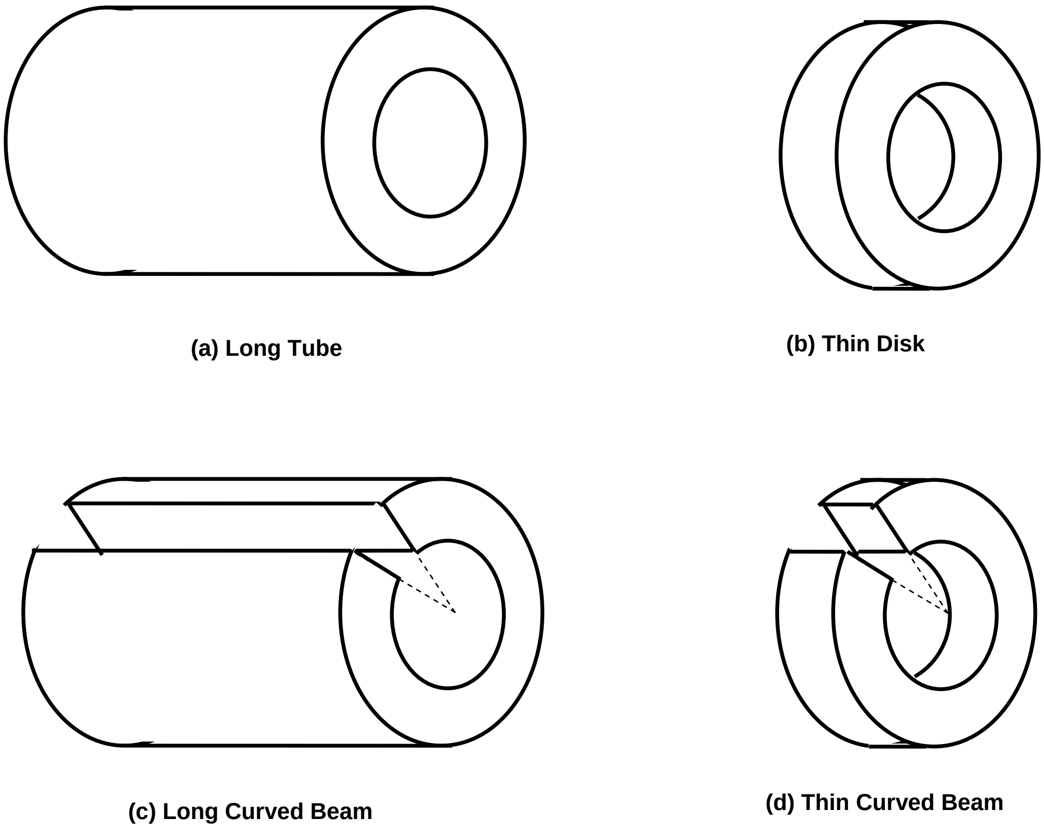


Figure 1: Autofrettaged tube cut to create curved beam and associated disks.

Reference [2] shows that (except in certain 'ideal' circumstances that do not conform to real gun tube geometries and materials) the hoop and radial residual stresses measured within a ring specimen cannot reliably determine those in the original tube. Ring cutting is predicted to cause a release of hoop and radial stresses of around 10-15% for 'ideal' hydraulic autofrettage [2]. But near-bore effects (due to Bauschinger effect) and the location of the original autofrettage radius create additional analytical complexity and hoop and radial stress release is then predicted to be approximately 9% [3].

One solution to this dilemma would be experimental determination of the axial stresses released during ring-cutting. This would then offer a direct route (via simple elastic superposition) to determine the full radial, hoop and axial stress profiles within the original gun tube. Knowledge of these stresses is essential in determining both fatigue lifetime and safe maximum pressure (SMP) of the tube.

The contour method (CM) is seen as a prime candidate for determining axial stresses within the tube and hence the radial and hoop stresses within the tube.

The CM involves careful cutting of a component, usually using electric discharge machining (EDM). The change in shape of the (previously flat) cut surface is quantified by accurate measurement of changes in height of the profile on the two mating halves of the new surfaces. These displacements are then averaged to eliminate various errors and input as displacements into an elastic finite element (FE) analysis which thereby recreates the pre-existing normal stresses.

The CM has been described in detail by Prime [4]. Its previous application has focused predominantly upon residual stresses in welds within singly-connected welded samples [5]. However a recent paper by Prime [6] describes its application to a doubly-connected region, namely a thin-walled tube with a girth weld.

The main experimental challenge during CM cutting is to minimize further yielding in order to ensure that the stress-relief process is essentially elastic. For the case of singly-connected regions this is frequently achieved by the use of constraints during cutting informed by a predictive process based upon numerical modelling of the planned cut in the form of a crack [5]. Stress intensity factors for this 'quasi crack' can then be used to predict the extent of the yielded zone to avoid significant re-yielding and damaging previously cut surfaces.

In the case of the thin-walled tube [6] Prime employed prior radial cutting to release significant hoop stresses. This caused the tube to spring open producing a long C-shaped specimen. The thin-walled nature of this specimen meant that the released bending moment was created by a hoop stress distribution that was effectively linear throughout the wall. The original residual stresses in this case were axi-symmetric but varied with axial position, being most significant near the weld.

By comparison, the autofrettaged tube is thick-walled with very high non-linear hoop stresses and is predominantly under 'engineering plane-strain' constraint, i.e. constant axial strain with zero net axial force and stresses constant along the length. When considering pressurized gun tubes this is often referred to as the 'open-end' condition. It is well-known that radial slicing of such tubes (or of disks cut from such tubes) results in the tube springing open, Figure 1(c). The opening angle may be used to calculate the total bending moment 'locked in' by autofrettage hoop stresses [7]. Such tests are frequently used in a simple quality control assessment of the overall autofrettage process.

In upcoming sections a procedure is developed for applying the CM to autofrettaged tubes.

Figure 1(a) shows a long, autofrettaged tube in a state of engineering plane-strain. When cut radially it springs open by angle, releasing a bending moment defined by the pre-existing hoop stresses, to create a long curved beam, Figure 1(c). In general the pre-existing hoop stresses released by the cut may take any form, provided they are self equilibrating (i.e. they produce zero net force across the wall). However St. Venant's principle applies and these released stresses rapidly redistribute themselves to create the analytic stress distribution associated with 'pure' or 'ideal' bending of a curved beam.

Timoshenko & Goodier, ref. [8], contains a detailed explanation of this behavior in Article 50, including an excellent photoelastic representation; this leads to the conclusion that the released 'ideal' stress field is established at a distance of one wall thickness (or beam depth) from the cut end of the beam. Ref [8] is based upon a plane stress analysis (i.e. zero axial stress). Under engineering plane-strain the 'ideal' principal stresses released within a curved beam take an analogous form defined in ref. [9]. This type of stress profile is employed in various superpositions in upcoming sections.

PREPARATORY ANALYSIS

The intention here is to explain, without mathematics, the limitations of CM as it applies to autofrettaged gun tubes and how these might be overcome.

The main challenge in applying CM is to ensure that EDM cutting induces minimal yielding. The issue is discussed in detail by Prime et al [4, 6] and Hosseinzadeh and Bouchard [5]. In essence, since an EDM cut resembles a straight-fronted crack progressing through the tube, stresses will be greatly magnified at the quasi-crack front and can cause local yielding which will invalidate the CM process which is based upon elastic material behavior during cutting.

In order to determine axial stresses within the tube the obvious first cut is normal to the axis of the tube. In this plane the cut, as it progresses, will concentrate axial stresses which modelling has predicted will be between 18% of yield in compression at the bore to 15% in tension at the OD. Hence significant yielding is possible during the initial cutting procedure, during which there will be high quasi-stress intensity. This is likely to decrease as the cut progresses, releasing some of the axial stresses, Figure 2. So the zone of the tube wall that experiences the initial cutting may not provide useful CM results, whilst the sector cut later in the process might provide useful results.

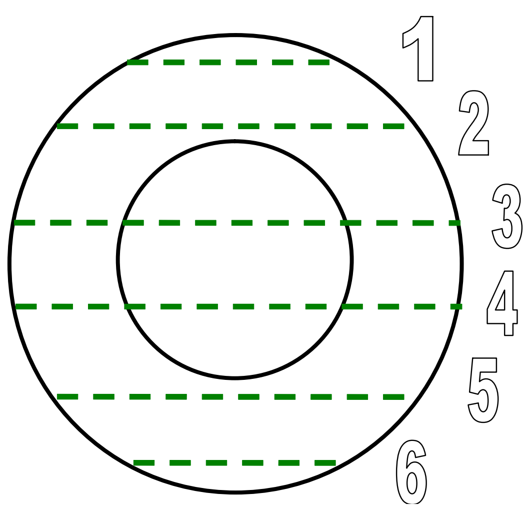


Figure 2: Diagram showing six stages of progression of EDM cut through the tube wall.

But since the displacements and associated stress fields that are sought are axi-symmetric, provided high quality contour results can be obtained over at least one continuous zone of the wall, encompassing bore through to OD, it should be possible to obtain useful measurements and hence pre-existing axial stresses via a single EDM cut.

But such an outcome is not certain, and a complementary procedure is required as a backup in the event of excessive yielding and to cross-check results. This 'indirect' route is now explained. It involves making a single radial cut, which need not be EDM, through the wall of the tube coincident with its axis. Such a procedure is frequently applied to thin rings extracted from a long tube. It results in the ring springing open by an angle to create a C-shaped specimen, Figure 1(d). The opening angle defines precisely the locked-in bending moment released as the hoop stresses across the cut are released [2,8]. This moment in turn defines the hoop and radial stresses released within the ring at a distance greater than one wall thickness (the St. Venant distance) from the cut [2].

An analogous argument applies when a long tube is sliced radially through the wall to create a long C-specimen. As explained previously, analogous equations define the relationship between opening angle and released hoop and radial stresses more than one St. Venant distance from the cut [2].

An example of the changes in the stress field is shown in Figure 3 taken from ref. [2]. The tube in this example has inner radius, a = 50mm, outer radius b= 100 mm. A723 gun steel with a yield strength (Y) of 1000 MPa is assumed with an autofrettage overstrain level of 70%. and Bauschinger effect is incorporated. This solution was obtained using the 'Hencky' numerical procedure described in ref. [10].

Figure 3 shows the hoop, radial and axial residual stresses in such a tube after hydraulic autofrettage. The bending moment locked in by hoop residuals was extracted and the resulting 'ideal' hoop, radial and axial stresses resulting from the cutting, acting beyond the St. Venant distance, were calculated . These ideal stresses were subtracted from the original autofrettage field; Figure 3 also shows the hoop and axial stresses remaining after a single radial cut to the tube. Clearly, the reduction in pre-existing stresses is very significant. Maximum hoop stress magnitude is reduced from 600 MPa to100 MPa and maximum axial stress magnitude from 170 MPa to 50 MPa. Equally importantly, likely SIF values for cracks traversing the specimen will be dramatically reduced, bringing associated benefits in reducing yielding during EDM cutting.

Crucially the slicing process involves a significant elastic reduction in maximum magnitude of axial stresses which means that any subsequent cutting normal to the tube axis is far less prone to yielding during cutting.

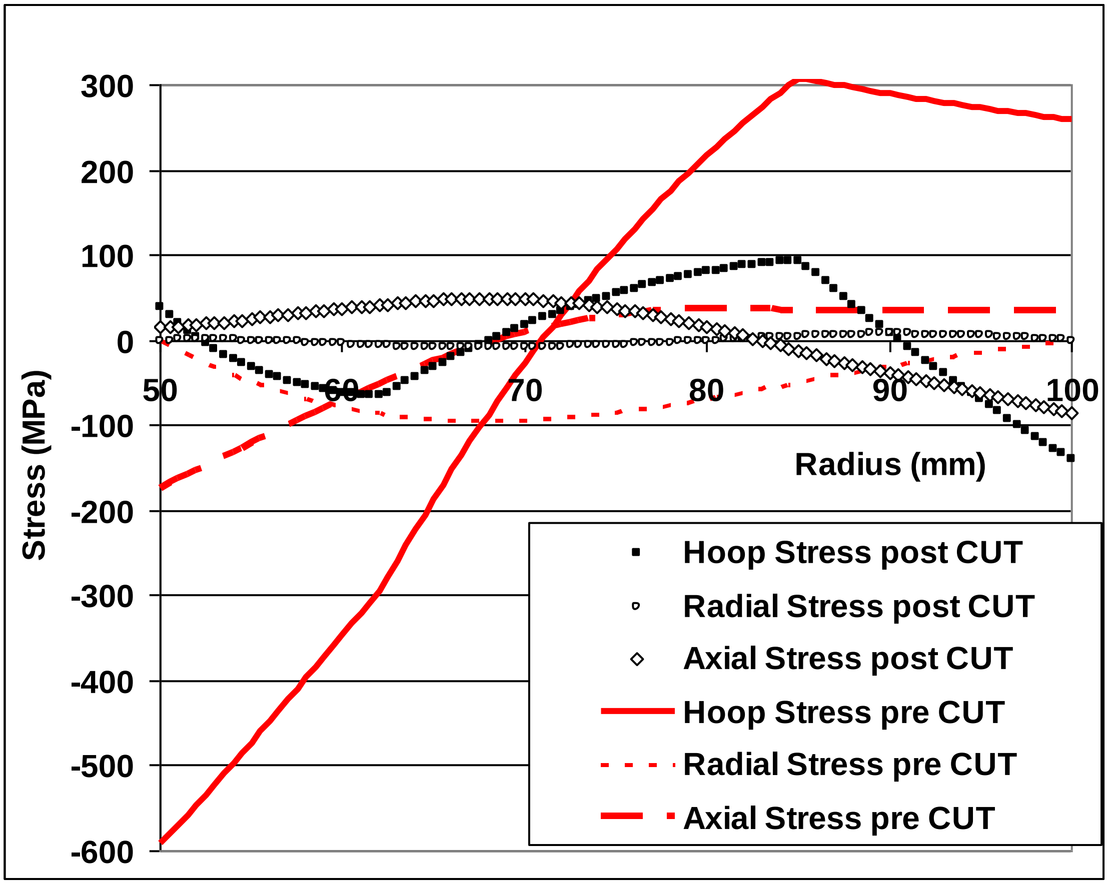


Figure 3: Hydraulic autofrettage of a long tube: Residual hoop, radial and axial stresses, 70% overstrain, numerical, open-end Autofrettage of A723 steel including non- linear Bauschinger re-yielding [8]. Intact tube labeled 'pre CUT', radially sliced tube labeled 'post CUT'.

EXPERIMENTAL EVIDENCE RELATING TO SWAGE AUTOFRETTAGE

Previous discussion herein related to hydraulically autofrettaged tubes. However many US gun tubes are swage-autofrettaged. Specimens from swaged tubes and from identical locations within those tubes equivalent to the proposed CM test specimens have already been tested using neutron diffraction (ND) and X-ray methods. ND results for hoop and radial stress are shown in Figure 4 [1]. These were obtained from quasi-plane stress thin disks cut from the tube – they therefore include the effects of 'killing' all axial stresses within the tube.

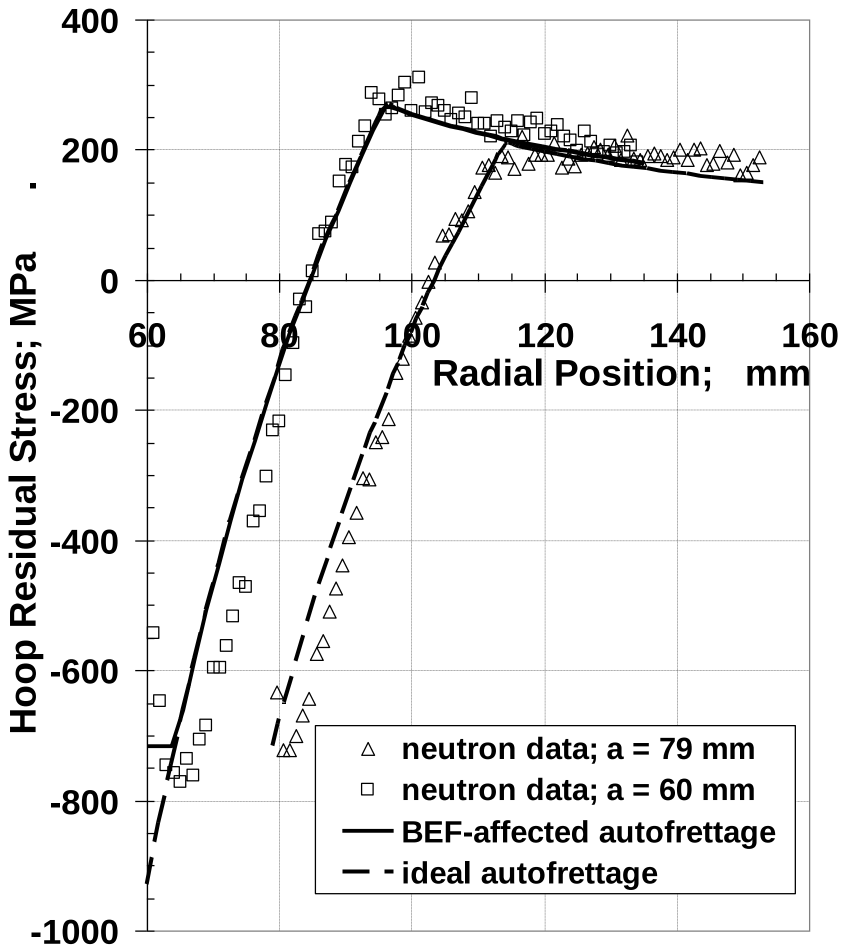
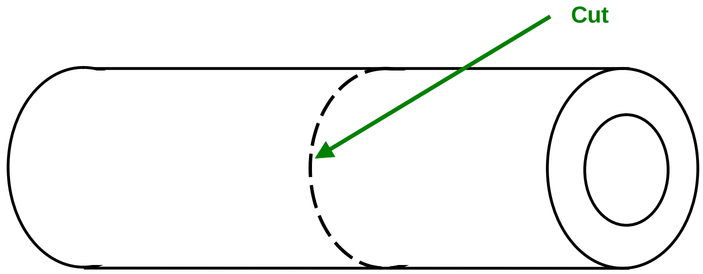


Figure 4: Measured hoop residual stresses for two thin ring sections of autofrettaged 1022 MPa yield strength tube, inner radii 60 mm and 79 mm compared to ideal hydraulic autofrettage of a tube. Ref [9].

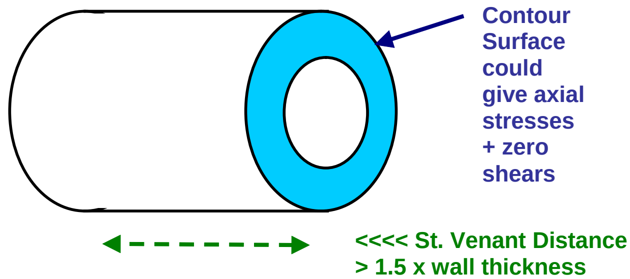
The experimental results clearly indicate that the hoop stresses within the thin ring specimens are similar (apart from near-bore effects) to the 'ideal' solution for hydraulic autofrettage of a long tube. Fundamental equilibrium requirements mean that the associated radial stress profile is also similar to the analogous 'ideal' solution.

PROPOSED EXPERIMENTAL PROCEDURE: CUTTING SEQUENCE AND ASSOCIATED LOGIC

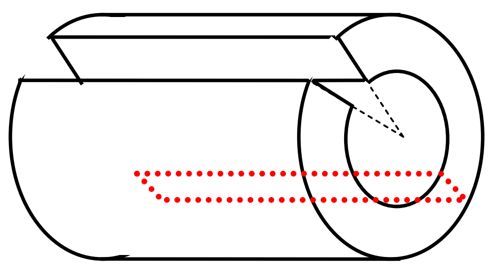
The proposed cuts and CM zones are shown in Figures 5 and 6. <u>The sequence of cutting and profiling is crucial to the procedure and must be observed!</u>



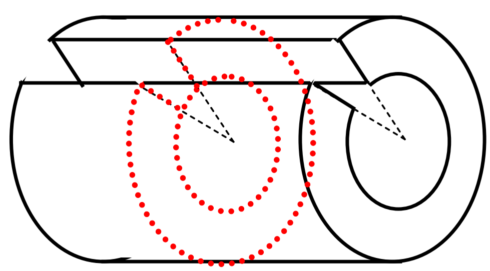
(a) Very Long Tube



(b) Two Long Tubes Cut



(c) First Long Curved Beam Sliced Radially Along Hatched Plane to Obtain Hoop Profile >> Stress
This surface could also give axials + radials via x-ray



(c) Second Long Curved Beam Sliced Circumferentially to Obtain Axial Profile >> Stress
This surface could also give hoops + radials via x-ray

Figure 5: General cutting procedure for initially very long tube.

Original Specimen

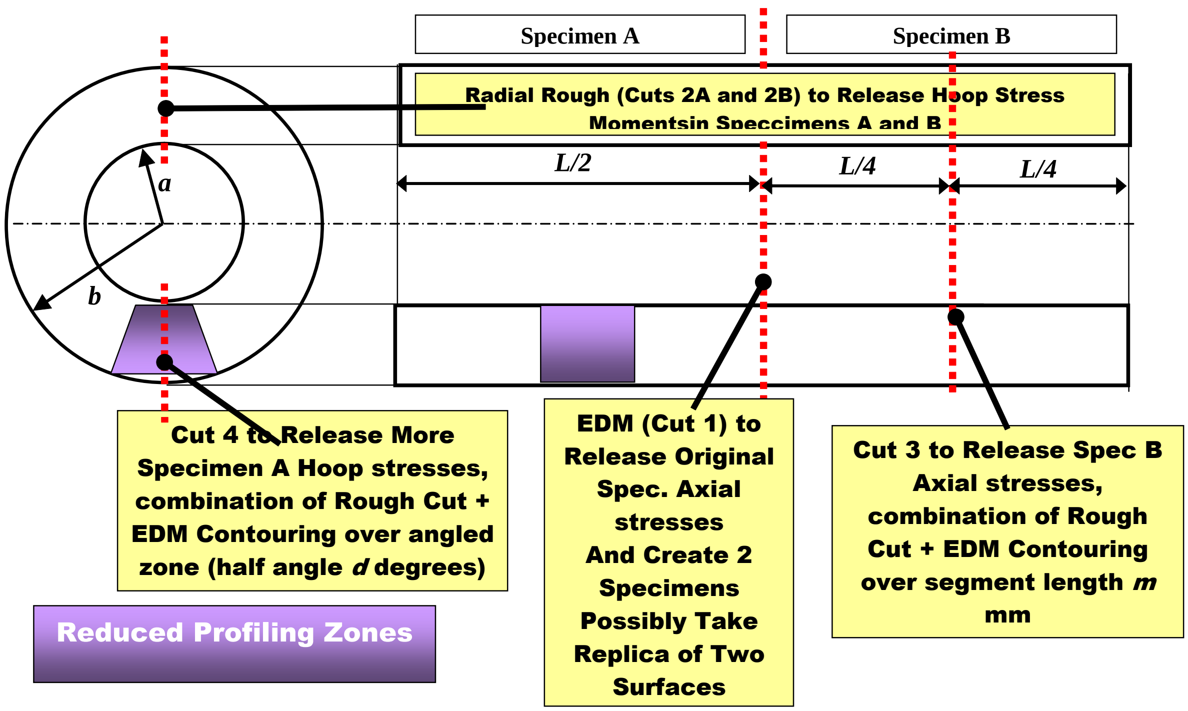


Figure 6: Cutting sequence for long autofrettaged tube.

There are two separate prospective test tube sections – they have different diameter ratios. This procedure applies to each of the tubes, the specific dimensions for the two tubes are presented in Table 1.

	Original Specimen #1		Original Specimen #2	
Original Specimen Length (L)	495 mm		419 mm	
Inner Radius (a)	60 mm		79 mm	
Outer Radius (b)	135 mm		154 mm	
	Sub Specimen		Sub Specimen	
	#1A	#1B	#2A	#2B
Min Half Angle *d* for EDM (axial stresses)		75 degrees		75 degrees
Min Length *m* for EDM (hoop stresses)	30 mm		50mm	

Table 1: Dimensions of original specimens and sub specimens.

SEQUENCE

1. The initial tube length is L, Figure 5.

2. Cut #1 is wholly EDM and cuts the tube into two halves, each of length L/2.

3. CM contouring of the two EDM cut surfaces to obtain axial stresses. Since the geometry is axi-symmetric it should only be necessary to take matching pairs of contours along radii. Possibly take pairs of contours at 10 degree intervals around entire cut surface? Calculate released axial stresses and select zone demonstrating least yielding during EDM cutting.

4. There are now two separate specimens, A and B (Figure 5). Cuts #2A and #2B can be non-EDM saw cuts, causing the tube to spring open (quite dramatically!) by an anticipated angle of approximately 4 degrees for typical overstrain levels.

5. At mid-length of specimens A and B measure the opening between the cut surfaces at the OD and subtract kerf of saw.

6. Specimen B: Cut #3 creates two C-shaped halves each of length L/4. This cutting should be EDM at least within *d* degrees of the vertical – it could be rough cut elsewhere.

7. Measure 20 pairs of contours within EDM zone on radii separated by equal angles. Calculate released axial stresses assuming axi-symmetric distribution around original tube. If sequence step #3 provides inaccurate results it may be repeated here.

8. Specimen A: Cut #4 creates two semi-circular halves. This cutting should be EDM within a minimum of *m* mm of the midpoint of the cut surface – it could be rough cut elsewhere.

9. Measure 20 pairs of parallel, equally- spaced contours within EDM zone. Calculate released hoop stresses.

LOGIC

Here numbering matches that in the ‘Sequence’ section above.

2. The EDM cut will presumably be straight, but in principle it could be circumferential if such a procedure is possible. Constraint would simply involve keeping the OD surface opposite the cut horizontal.

3. The pre-existing axial stresses (from a hydraulic autofrettage numerical solution) are compressive (-150 MPa) at ID rising smoothly to +40 MPa at OD. Thinking in terms of resulting quasi stress intensity factors, this suggests that a straight EDM cut thru such an axi-symmetric profile will provide some radial lines that are free of significant yielding. Only a few such zones are required to obtain a convincing solution. Crucially, if this solution can be achieved it can immediately be combined with neutron diffraction (ND) and/or X-ray results for thin (quasi

plane stress) disks cut from an identical tube to predict all stresses in tube. However, if yielding during cutting makes this impossible, the remainder of this procedure, involving axial slicing to release the hoop stresses and associated bending moment, should still provide acceptable results.

4. PRIOR TO THIS CUT it might aid our understanding to apply axial and hoop strain gauges to the OD of specimens A and B diametrically opposite the cut line at the mid length of each specimen. Note that any further cutting after hoop stresses have been contoured following sequence steps 2 and 3 above will destroy that contour. It cannot be recreated!

5. As explained in 'Preparatory Analysis' section, this opening can be converted analytically to an angle and hence to a released bending moment and hence to released hoop, radial and axial stresses.

6. The sector over which contours may be taken is defined by the region that is beyond the relevant St. Venant distance and hence can be treated elastically in subsequent axi-symmetric superpositions.

8. Again, the sector over which contours may be taken is defined by the region that is beyond the relevant St. Venant distance and hence can be treated elastically in subsequent axi-symmetric superpositions.

SUMMARY AND CONCLUSIONS

Experimental measurement of residual stresses within pressure vessels, in particular gun tubes, has made good progress over the past six years. The common feature of these experiments is that they were conducted on axially thin (quasi plane stress) ring specimens cut from much longer gun tubes

But extracting specimens in this way means that axial stress in the tube is unknown. Furthermore, such ring cutting which eliminates axial stress also alters the hoop and radial residual stress fields. This means that hoop and radial stresses in the ring differ from those in the original tube.

One solution to this dilemma would be experimental determination of the axial stresses released during ring-cutting. This would then offer a direct route (via simple elastic superposition) to determine the full radial, hoop and axial stress profiles within the original gun tube. Knowledge of these stresses is essential in determining both fatigue lifetime and safe maximum pressure (SMP) of the tube.

The contour method (CM) is seen as a prime candidate for determining axial stresses within the tube and hence the radial and hoop stresses within the tube. The CM involves careful cutting of a component, usually using electric discharge machining (EDM). The change in shape of the (previously flat) cut surface is quantified by accurate measurement of changes in height profile on the two mating halves of the new surfaces. These displacements are then averaged to eliminate various errors and input as displacements into an elastic finite element (FE) analysis which thereby recreates the pre-existing normal stresses.

The main experimental challenge during CM cutting is to minimize further yielding in order to ensure that the stress-relief process is essentially elastic.

In this paper a procedure was developed for applying the CM to autofrettaged tubes.

In order to determine axial stresses within the tube the obvious first cut is normal to the axis of the tube. In this plane the cut, as it progresses, will concentrate axial stresses which are expected to range between 18% of yield in compression at the bore to 15% in tension at the OD.

So the zone of the tube wall that experiences the initial cutting may not provide useful CM results, whilst the sector cut later in the process might provide useful results. Provided high quality contour results can be obtained over at least one continuous zone of the wall, encompassing bore through to OD, it should be possible to obtain useful measurements and hence pre-existing axial stresses via a single EDM cut.

But such an outcome is not certain, and a complementary procedure is required which will allow recovery of axial residual stress.

This involves slicing the tube radially coincident with the tube axis to create a long C-specimen. The opening angle defines precisely the locked-in bending moment released as the hoop stresses across the cut are released. An example of the changes in the stress field is shown in the paper. The reduction in pre-existing stresses is very significant. Maximum hoop stress magnitude is reduced from 600 MPa to100 MPa and maximum axial stress magnitude from 170 MPa to 50 MPa. Pre-existing hoop and radial stresses may then be obtained from a combination of superposition and use of CM.

In the case of swage autofrettage hoop stresses within thin ring specimens are similar (apart from near-bore effects) to the ‘ideal’ solution for hydraulic autofrettage of a long tube. This in turn suggests that the CM procedures proposed herein on the basis of hydraulic autofrettage models should be equally applicable to swage autofrettaged tubes.

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